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15 Years Going Steady – Timing the Magnetar 1E 1841-045

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Abstract. We report on a long-term monitoring campaign of 1E 1841–045, the 12-s anomalous X-ray pulsar and magnetar candidate at the center of the supernova remnant Kes 73. We have obtained approximately monthly observations of the pulsar with the *Rossi X-ray Timing Explorer (RXTE)* spanning over two years, during which time 1E 1841–045 is found to be rotating with sufficient stability to derive a phase-connected timing solution. A linear ephemeris is consistent with observations of the pulse period made over the last 15 yrs with the *Ginga*, *ASCA*, *RXTE*, & *BeppoSAX* observatories. Phase residuals suggest the presence of “timing noise”, as is typically observed from young radio pulsars. These results confirm a rapid, constant spin-down for the pulsar, which continues to maintain a steady flux; this is inconsistent with most accretion scenarios.

1. Introduction

1E 1841–045 is perhaps the best candidate for a magnetar – an isolated neutron star (NS) with an extreme magnetic field whose energy loss is dominated by magnetic field decay (Vasisht & Gotthelf 1997; see Duncan & Thompson 1992 for theory of magnetars). This interpretation is based primarily on initial studies which showed that the pulsar is slowing down rapidly ($\dot{P} = 4.1 \times 10^{-11}$ s/s), with an inferred equivalent magnetic dipole field of $B_p \sim 7.0 \times 10^{14}$ G, nearly twenty times the quantum critical field, while producing steady emission at a rate far in excess of its rotational kinetic energy loss (Vasisht & Gotthelf 1997). Further evidence for an isolated system is the absence of Doppler shifts, detectable companion or accretion disk, and a spectrum which differs greatly from those of known accretion-powered binary systems.

Here we report on a two-year monitoring campaign of 1E 1841–045 made with *RXTE*. We have obtained a spin ephemeris derived from a phase-connected timing solution which is found to be consistent with nearly two decades of observations of the pulsar. We are able to characterize rotational stability of 1E 1841–045, including a search for timing noise, pulsed flux variability, and frequency glitches. These results provide important observational constraints on both the magnetar and any accretion model for 1E 1841–045.

2. Observations and Results

We acquired a total of 45 observations of 1E 1841–045, spaced nearly uniformly, during the interval spanning 1999 February 15 through 2001 April 2, with a typical observation lasting ~ 7 ks. These observations were made with the Proportional Counter Array (PCA; Jahoda et al. 1996) aboard *RXTE*. The PCA consists of 5 collimated proportional counter units (PCUs) with a total effective area of $\sim 6500 \text{ cm}^2$ in the energy range 2 – 60 keV and a resolution of $\sim 18\%$ at 6 keV over its $\sim 1^\circ$ field of view (FWHM).

Data were collected in `GoodXenonwithPropane` data mode with the photon arrival times recorded at 1 μs resolution and the energy binned into 256 spectral channels. To maximize the signal-to-noise ratio of the pulsar given the spectral properties of the source and background we restricted the energy range to 2.1–5.4 keV and used events from the top Xenon layer only. All arrival times were corrected to the solar system barycenter.

To determine the average pulse time-of-arrival (TOA) for each observation we folded the photon arrival times into 32 bins modulo the test frequency. This frequency was determined initially from a Fast Fourier transform and later from an approximate timing ephemeris. The resulting pulse profiles were then cross-correlated with a high signal-to-noise template and the measured TOAs fitted to a polynomial using the `TEMPO` timing software package. The uncertainty on the best-fit model parameters, the pulse frequency ν and its time derivatives, were small enough to allow prediction of the phase of the next observation to within ~ 0.2 , given the spacing of our monitoring observations. This is only practical for a very stable rotator.

Figure 1 presents the results of our fit. Complete modeling of the pulse arrival times required four time derivatives of ν to produce residuals from this fit whose RMS variability are comparable with the TOA arrival times uncertainties. These residuals, defined as the difference between the observed and model-predicted pulse arrival times, have RMS deviations of only 3% of the pulse period. We find that 1E 1841–045 has maintained phase coherence over the 2 year duration of our observations with no indication of any glitch activity, i.e., no sudden changes in the pulse period. The data are well modeled for all but three observations which took place near the start of our monitoring campaign. These $\sim 5\sigma$ points, however, deviate by only a small fraction of the pulse period. For all cases, we estimated the uncertainties on the pulse arrival times by means of Monte-Carlo simulations of the pulse profiles.

In Figure 2, we compare our derived ephemeris with pulse frequency measurements spanning 15 yrs obtained with the *Ginga*, *ASCA*, *RXTE*, & *BeppoSAX* observatories as reported in Gotthelf et al. (1999). Despite the need for four

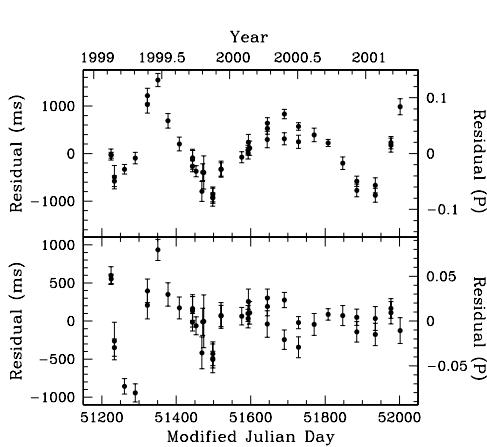


Figure 1. Arrival time residuals for the 12 s pulsar 1E 1841-045 in Kes 73 versus epoch. (Top panel) Residuals after removing the leading 3 frequency derivative terms from the phase-connected *RXTE* ephemeris. Evidently there is much “timing noise” characteristic of young radio pulsars. (Bottom panel) The arrival time residuals using an ephemeris with four frequency derivatives. The RMS residuals from the final fit is $\pm 3\%$ of the pulse period. Three data points are found to differ from the mean by $\sim 5\sigma$.

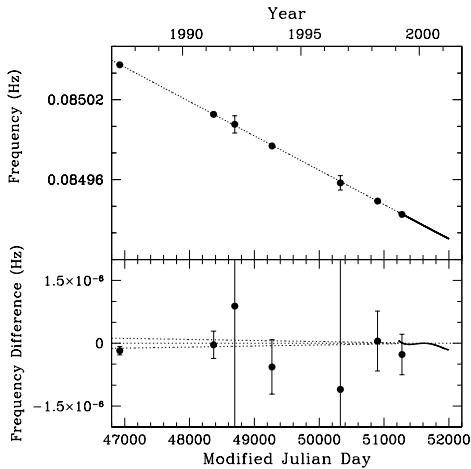


Figure 2. The spin-down history of 1E 1841-045 and its residuals from a *linear* ephemeris (thick solid line). The filled circles show the previously observed spin frequencies (from Gotthelf et al. 1999). The linear terms of the phase-connected ephemeris, when extrapolated over 10 years (dotted line), is found to be consistent with the previous measurements, despite its appreciable timing noise. The uncertainty in the extrapolation is comparable the width of the dotted line.

frequency derivatives to fully model the pulse arrival times, the linear ephemeris “predicts” the historic data consistent with their measured errors; in contrast, when higher order derivatives are included in the ephemeris, large departures from the earlier data points result. We conclude that these higher order terms ($> \dot{\nu}$) are likely random wandering of the timing residuals about an otherwise very stable, constant spin-down. Timing residuals of this nature are often measured for radio pulsars and are generally referred to as radio “timing noise” (see, e.g., Cordes & Helfand 1980). The magnitude of second derivative gives the strength of the timing noise observed from 1E 1841-045.

3. Discussion

Observationally 1E 1841-045 is characterized as an Anomalous X-ray Pulsar (AXP; see Mereghetti 2001 for a review). This small group (~ 6 members) of seemingly isolated pulsars are observed exclusively in the X-ray energy band¹, are underluminous for an accreting X-ray binary system, and are, except for the characteristic burst activity, otherwise similar observationally to the SGRs. This

¹There is recent evidence for IR emission from two AXPs, see Hulleman et al 2000, 2001.

is the fourth AXP, after 1E 2259+586, 1E 0142+615, and RXS J1708–4009, for which long-term phase-connected timing is possible, characterizing these objects as rotators of great stability (see Gavriil & Kaspi 2001). In contrast, the AXP 1E 1048.1–5937 is much less stable, as a phase-connected timing solution cannot be maintained for more than a few months (Kaspi et al. 2001). The measured strength of the torque noise for 1E 1841–045 is comparable to that found for 1E 1048.1–5937, during its intervals of relative stability, but substantially weaker than the torque noise measured for most accreting pulsars (Bildsten et al. 1997). Still, it is a factor of two quieter than even the most exceptionally quiet accreting pulsars (e.g., 4U 1626–67, Chakrabarty et al. 1997).

The leading theory for the nature of AXPs is the magnetar model as first proposed by Thompson & Duncan (1996). In this model, in the absence of soft-gamma-repeater-like outbursts, one expects generally smooth spin-down. The lack of deviations from a simple spin-down model found for 1E 1841–045 is consistent with the magnetar model. An alternative model proposed for AXPs is that they are accreting from a disk of material that formed shortly after the supernova explosion that gave birth to the neutron star. Severe constraints have been placed on the plausibility of this scenario by optical/IR observations of AXPs (Hulleman et al. 2000). Both the constant, long-term spin-down of 1E 1841–045, as well as the fact that phase-connected timing is possible for this source, provide evidence against accretion scenarios, as spin-up episodes, as well as considerably more torque noise, are in general to be expected.

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